NASA TT F-9365

NASA TT F-9365

EFFECT OF HYDROGEN ON THE MECHANICAL PROPERTIES OF TITANIUM AND OT4-1 ALLOY

V. A. Livanov, A. A. Bukhanova, B. A. Kolachev,
N. P. Neverova-Skobeleva, I. I. Slavina,
B. E. Sheynin, and L. V. Shcherbina

Translation of "Vliyaniye vodoroda na mekhanicheskiye svoystva titana i splava OT4-1." Izvestiya Vysshikh Uchebnykh Zavedeniy - Tsvetnaya Metallurgiya, Vol. 7, No. 4, pp. 124-129, 1964.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON MAY 1965

EFFECT OF HYDROGEN ON THE MECHANICAL PROPERTIES OF TITANIUM AND OT4-1 ALLOY

Moscow Aviation Technology Institute,
Department of Metallography and Heat Treatment Technology

ABSTRACT

23716

Tests to determine the effect of hydrogen impurity on the mechanical properties of titanium and a low alloy of titanium are described. It turns out that the property most affected by increased hydrogen content is the ductility, which increases the embrittlement and fracture tendency of these metals under dynamic loading. The situation is alleviated, however, by heat treatment at 900°C with quenching in air or water.

It is found that existing Soviet norms for the maximum permissible ductility of the tested metals are not adequate to ensure passable ductility values. Nor is it certain, if the properties are improved by heat treatment, just how stable they will remain with aging. Further investigations are indicated.

AUTHOR

It is assumed at the present time that the ductility of a metal is largely /124* characterized by the tendency of mechanical parts toward brittle fracture under dynamic loading (ref. 1).

The most suitable of Soviet-made titanium alloys for parts to operate under dynamic loading are the low alloy types OT4-1 (1.0-2.5% Al, 0.8-2% Mn) and

---

*Numbers in the margin indicate pagination in the original foreign text.

OT4 (2-3.5% Al,).8-2% Mn), which possess the greatest (apart from commercial titanium) ductility. The manufacturer's certified ductility values for these alloys in the annealed state lies within the very broad limits of 3.5-6.5 kg/cm^2 for the OT4 alloy and 5-10 kg/cm^2 for the OT4-1 alloy.

One of the possible causes for the considerable spread in ductility values is hydrogen embrittlement, which is observed in low alloys of the system Ti-Al-Mn, for both low and high strain rates (refs. 1 and 2). Moreover, with a hydrogen content on the order of 0.015% in OT4 alloy, i.e., at the upper limit of admissible concentrations by technical standards, the tendency for cold cracks to form after welding has been observed (ref. 3). Consequently, in evaluating the possibility of using OT4 and OT4-1 alloys under a particular set of operating conditions, the influence of hydrogen on the tendency of these alloys toward brittle fracture must be accorded special attention.

The objective of the present investigation was to ascertain the influence of hydrogen on the mechanical properties of OT4-1 alloy, particularly on the ductility, and to establish the ultimate permissible hydrogen content for which the metal will still maintain a high resistance to brittle fracture. For the sake of comparison, tests on commercially pure titanium, type VT1-1, were run according to the same procedure.

The OT4-1 alloy and VT1-1 titanium were prepared from industrial melts in an oven with a capacity of 0.5 . The chemical composition and mechanical properties of the investigated materials are shown in tables 1 and 2.

The ingots were forged into plates with dimensions 40 x 200 x 400 mm, from which blanks were cut out under a pattern, with allowance for polishing. All of the blanks were subjected to vacuum annealing at 900°C for six hours, after which they were saturated with hydrogen at 880°C and oven-cooled at a rate of about 80 deg/hr, resulting in a final material with an almost equilibrium state.

The principal part of the investigation was conducted with the pure titanium and OT4-1 alloy in the annealed state, except for certain special /125 cases as indicated.

TABLE 1

CHEMICAL COMPOSITION OF THE TEST MATERIALS								
Material	Content, %							
	Al	Mn	H_2	N_2	C	Fe	Si	O_2
VT1-1	-	--	0.007	0.0015	0.012	0.06	0.045	0.013
OT4-1	2.4	1.11	0.008	0.030	0.030	0.09	0.07	---

TABLE 2

MECHANICAL PROPERTIES OF THE TEST MATERIALS (FORGED BAR WITH CROSS SECTION 14 x 14 mm)				
Material	Mechanical properties			
	σ_T kg/mm^2	δ, %	ψ, %	a_κ kg/mm^2
VT1-1	49.7	26.0	59.3	13.9
OT4-1	76.9	17.2	50.1	6.2

Static tensile tests were performed on the metal with different contents of hydrogen, moving the traverse of the tensile testing machine at standard rates (2 to 4 mm/min), along with ductility tests, using the appropriate equipment and standard samples.

It is evident from the data of table 3 that increasing the hydrogen content to 0.032% in commercial titanium and to 0.015% in OT4-1 alloy elicits essentially no change in the normal mechanical properties of the materials, except in the ductility.

TABLE 3

MECHANICAL PROPERTIES VS. HYDROGEN CONTENT OF THE TEST MATERIALS

Material	H content, % by wt.	Rockwell hardness	σ_T kg/mm^2	δ, %	ψ, %	a_K kg/mm^2
Scale B						
VT1-1	0.0044	82	49.4	27.0	58.0	15.5
	0.0073	79	45.3	29.2	68.2	6.8
	0.017	85	50.8	29.5	48.6	2.0
	0.032	80.5	45.5	25.8	58.9	0.25
	0.6	81.3	not determined			0.4
Scale C						
OT4-1	0.006	21	08.7	13.8	31.6	3.3
	0.015	20	70.1	14.5	20.0	1.1
	0.6	24	73.4	1.5	2.3	0.3

Note: The mechanical properties were determined from test data for 3 or 4 samples.

However, increasing the hydrogen content to 0.1% sharply lowers the plastic properties of the OT4-1 alloy.

The characteristic most sensitive to changes in the hydrogen content turns out to be the ductility. Increasing the hydrogen content to 0.015-0.017% greatly lowers the ductility of both commercial titanium and OT4-1 alloy (more than sevenfold relative to the vacuum annealed samples). Consequently, the maximum hydrogen content permissible by technical standards (0.015%) does not guarantee satisfactory ductility on the part of commercial titanium or OT4-1 alloy.

An analysis of breaks in impact-tested samples (fig. 1) shows that the observed reduction in ductility with increasing hydrogen content is accompanied by enlargement of the fracture facets.[1] In commercial titanium, this is related to an increase in the dimensions of the hydride precipitates, which are essentially internal incipinet crevices, along which fracture occurs. With a hydrogen content as high as 0.032%, the hydride phase in commercial titanium is located primarily along the grain boundaries. With a high hydrogen content (0.1%), it emerges in the form of flakes, predominantly inside the grain (fig. 2).

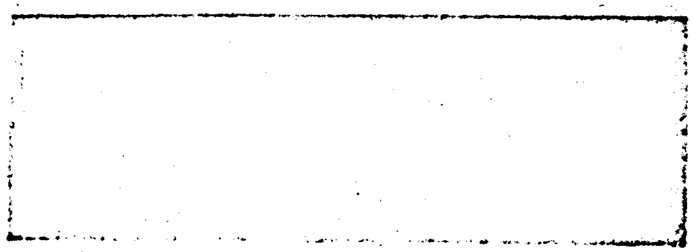

Figure 1. Fractures of Impact-tested Samples of Alloy OT4-1 with a Hydrogen Content of 0.006% (a) and ~ 0.1% (b). X1.5

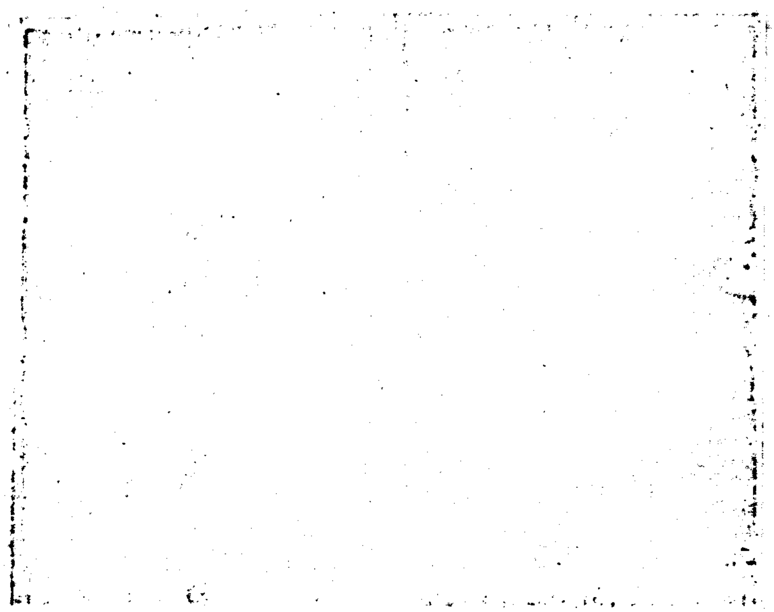

Figure 2. Microstructure of Alloy VT1-1 with a Hydrogen Content of 0.032%, x 400 (a), and ~ 0.1%. x 90 (b).

[1] By facets we mean the surfaces along which rupture of the sample occurs.

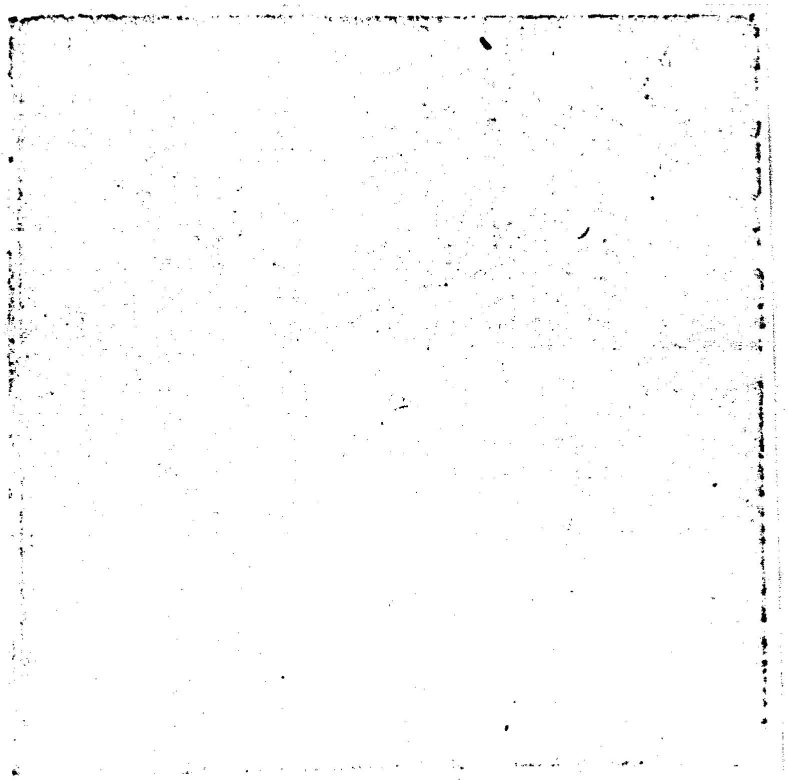

Figure 3. Microstructure of Alloy OT4-1 with Various Hydrogen Contents:

a) after vacuum anneal (α-phase with streaks of β-phase);

b) 0.013% (hydride flakes along streaks of β-phase);

c) 0.1%;

d) the same in dark field, the arrows indicating the hydride phase at interface between α- and β-phases;

e) 0.024%, treatment at 900°C with cooling in water;

f) the same with cooling in air.

a, b, e, f) x 400; c, d) x 600.

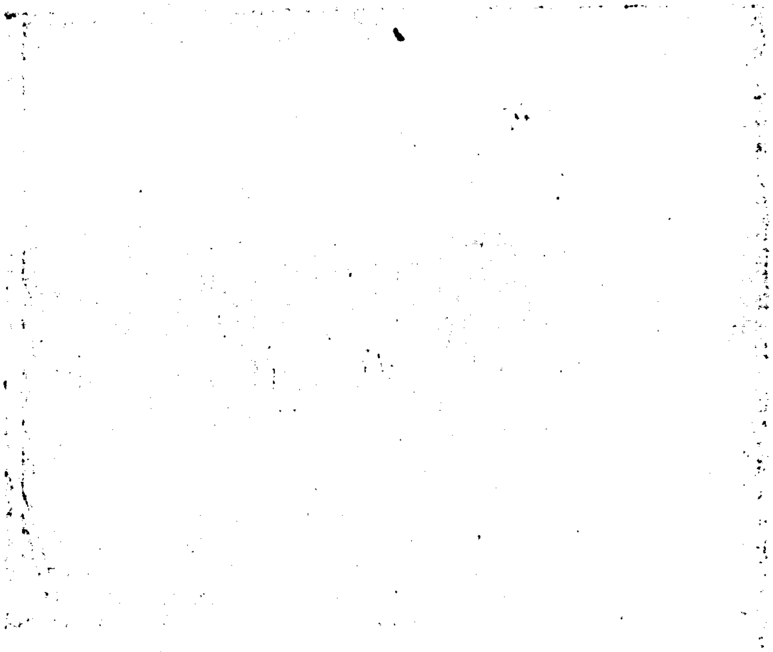

Figure 4. Microstructure at the Fracture Surface of OT4-1 Alloy Sample With a Hydrogen Content of 0.006% (a) and ~ 0.1% (b). x 400.

After annealing, the OT4-1 alloy has a structure consisting of elongated /126 flakes of α-phase, along the boundaries of which occurs a second phase; according to the data of X-ray structural analysis, this phase is a β-solid folution. When examined under the microscope, it has a bright coloring and clearly defined boundaries (fig. 3a), which also show up well in a dark field.

With a higher content of hydrogen, dark-etched hydride precipitates appear at the boundaries between the indicated phases, their number increasing as the hydrogen content is increased (see figs. 3b, 3c). A photograph taken in a dark field discloses that the hydride phase occurs at the boundary between the α- and β-phases (see fig. 3d).

The fracture of ductile samples of OT4-1 alloy subjected to vacuum annealing occurs predominantly through the body of the grain, giving rise to considerable plastic deformation of the metal (fig. 4a). In samples of VT4-1 alloy with a high hydrogen content (~0.1%), fracture proceeds in large measure along the boundaries of the former grain of the β-phase. In this case, plastic deformation of the flakes of α- and β-phase is not observed (see fig. 4n).

It is known that the hydrogen embrittlement of titanium and its alloys can be abated by heat treatment. It was noted in our investigations that heating of the OT4-1 alloy to 900°C with subsequent cooling in water or air sharply raises the ductility, even with a 0.024% H-content, which far exceeds the permissible limit for its content by technical standards (fig. 5).

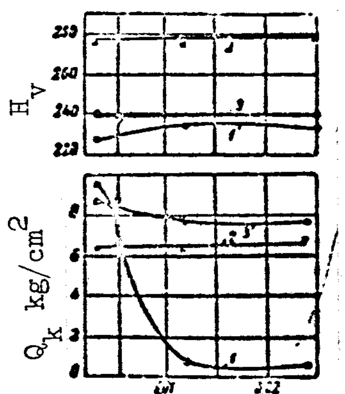

Figure 5. Influence of Hydrogen on the Ductility and Hardness of OT4-1 Alloy After Cooling From 900°C in the Oven (1), in Water (2), and in Air (3).

After cooling in water from a temperature of 900°C, the structure of the metal comprises two phases: a residual α-phase and a martensite α'-phase (see fig. 3e). The presence of the α'-phase in the structure causes greater hardness and somewhat lower values for the ductility relative to the metal cooled in air. The structure of the metal cooled in air comprises flakes of the α-phase /127 (see fig. 3f) with interjacent portions of a second phase, which is clearly β-solid solution. The number of hydride flakes after heat treatment with cooling in air and especially in water is considerably less than in the annealed samples.

The tests that gave the results shown in figure 5 were conducted from 10 to 15 days after heat treatment of the samples. However, in the course of natural or artificial aging of the quenched titanium alloys, it was possible for their plastic attributes to be diminished.

As shown by the data in table 4, OT4-1 alloy with an average hydrogen content of 0.008%, quenched in water from a temperature of 900°C, actually increases in strength after six-day aging and has lower values for the relative alongation and ductility by comparison with the same alloy subjected to vacuum annealing.

TABLE 4

CHANGE IN THE MECHANICAL PROPERTIES OF OT4-1 ALLOY AFTER HEAT TREATMENT

Heat treatment conditions	Aging conditions	Mechanical Properties				
		σ_T kg/mm^2	δ, %	ψ, %	H_V	a_K kg/mm^2
Vacuum annealing at 900° for 6 hr		68.7	13.8	31.6	229	9.5
900° for 30 min, cooling in water	without aging	73.2	14.3	33.7	269	8.3
	60 hr at 300°	79.0	9.5	25.2	277	7.2
900° for 30 min. cooling in air	without aging	69.3	16.1	40.8	229	10.7
	60 hr at 300°	70.2	14.5	40.1	248	9.1

Artificial aging of OT4-1 alloy from the same melt, first normalized at 900°, did not bring about any reduction in the plasticity characteristics; the /128 ductility in this case was lowered by 1.5 kg/mm^2, yet stayed at the level of the vacuum annealed metal.

A diminution did not occur in the plasticity or ductility of the metal in large forged pieces of TR4-1 alloy subjected to normalization under the given conditions, nor in the course of subsequent aging in the atmosphere for one year (see table 5).

TABLE 5

MECHANICAL PROPERTIES OF FORGED PIECES OF OT4-1 ALLOY SUBJECTED TO ONE-HOUR NORMALIZATION AT 900°, AFTER AGING UNDER ATMOSPHERIC CONDITIONS FOR ONE YEAR

Percentage of basic alloying elements		H-content % wt.	Test period	Mechanical properties			
Al	Mn			σ_T kg/mm^2	δ, %	ψ, %	α_K kg/mm^2
1.26	0.94	0.005	before aging	58.7	19.4	40.5	10.3
			after aging	57.0	17.0	38.2	0.8
1.8	1.2	0.007	before aging	59.5	18.4	38.6	9.7
			after aging	58.6	18.2	30.5	9.1

However, these data refer only to metal with a hydrogen content less than 0.010%.

The problem of stability of the plasticity and viscosity during aging of forged or normalized OT4-1 alloy containing 0.015% hydrogen or more will require additional investigations.

CONCLUSIONS

1. Of all the properties investigated, the ductility of VT1-1 and OT4-1 alloys is the most sensitive to changes in the hydrogen content. The brittle fracture tendency of the investigated titanium alloys under dynamic loading, being associated mainly with the ductility, turns out to be smaller, the lower the content of hydrogen in the metal.

2. The upper limit established according to existing technical specifications for the hydrogen content in VT1-1 and OT4-1 alloys (0.015%) does not guarantee the required ductility. Additional investigations using data existing at the plant on the ductility of melts with different hydrogen contents will be required in order to establish the admissible hydrogen content in these alloys.

3. Heating of the OT4-1 alloy to 900° with subsequent cooling in air or water makes it possible to attenuate the detrimental effects of hydrogen on the ductility (its content within the limits up to 0.01% that we investigated). However, additional experiments will be required to study the permanency in natural and artificial aging of the properties acquired by heat treatment.

REFERENCES /129

1. Livanov, V. A., Bukhanova, A. A. and B. A. Kolachev. Hydrogen in Titanium (Vodorod v titane). Metallurgizdat (Ferrous and Nonferrous Metallurgy Publishing House), 1962.

2. Haynes, R. J. Inst. Metals, Vol. 89, No. 7, p. 249, 1961.

3. Mikhaylov, A. S. and B. S. Krylov. Metallovedeniye i Termicheskaya Obrabotka Metallov, No. 4, p. 48, 1962. English translation: Metals Science and Heat Treatment of Metals, No. 4, p. 166, 1962.

Received 30 August 1963

Translated for NASA by Stemar Engineering, Inc.
4940 Long Beach Blvd., Long Beach, California.